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# Using Groundwater Age and Other Isotopic Signatures to Delineate Groundwater Flow and Stratification

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# USING GROUNDWATER AGE AND OTHER ISOTOPIC SIGNATURES TO DELINEATE GROUNDWATER FLOW AND STRATIFICATION

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## Introduction

Isotopic tracers, such as stable isotopes of the water molecule and tritium, have been used in investigations of groundwater flow and transport and recharge water source for several decades. While these data can place hard constraints on groundwater flow rates, the degree of vertical flow between aquifers and across aquitards, and recharge source area(s), they are rarely used, even for validation, in conceptual or numerical models of groundwater flow. The Groundwater Ambient Monitoring and Assessment Program, sponsored by the California State Water Resources Control Board, and carried out in collaboration with the U.S. Geological Survey, has provided the means to gather an unprecedented number of tritium-helium groundwater ages in the basins of California. As the examples below illustrate, a collection of groundwater ages in a basin allows delineation of recharge areas (youngest ages), bulk flow rates and flowpaths, as well as a means of assessing susceptibility to anthropogenic contaminants.

## Groundwater Age-Dating Technique

Tritium ($^3H$) is a very low abundance (around 1 part in $10^{17}$ of total hydrogen), radioactive isotope of hydrogen with a half-life of 12.34 years. Atmospheric nuclear weapons testing in the 1950's and early 1960's released tritium to the atmosphere at levels several orders of magnitude above the background concentration (figure 1). This atmospheric tritium enters groundwater (as HTO, with one hydrogen atom as tritium) during recharge. Its concentration in groundwater decreases by radioactive decay, dilution with non-tritiated groundwater, and dispersion. While the presence of tritium is an excellent indicator of water that recharged less than about 50 years ago, age dating groundwater using tritium alone results in large uncertainties due to spatial and temporal variation in the initial tritium at recharge. Measurement of both tritium and its daughter product helium-3 ($^3He$) allows calculation of the initial tritium present at the time of recharge (figure 2), and ages can be determined from the following relationship:

$$\text{Groundwater Age (years)} = -17.8 \times \ln\left(1 + {}^3He_{trit}/{}^3H\right)$$

The age measures the time since the water sample was last in contact with the atmosphere. The $^3He_{trit}$ indicated in the equation is the component of $^3He$ that is due to the decay of tritium. Methodologies have been developed for correcting for other sources of $^3He$, such as the earth's atmosphere and potential small contributions from thorium and uranium decay (Aesbach-Hertig et al., 1999; Ekwurzel et al., 1994).

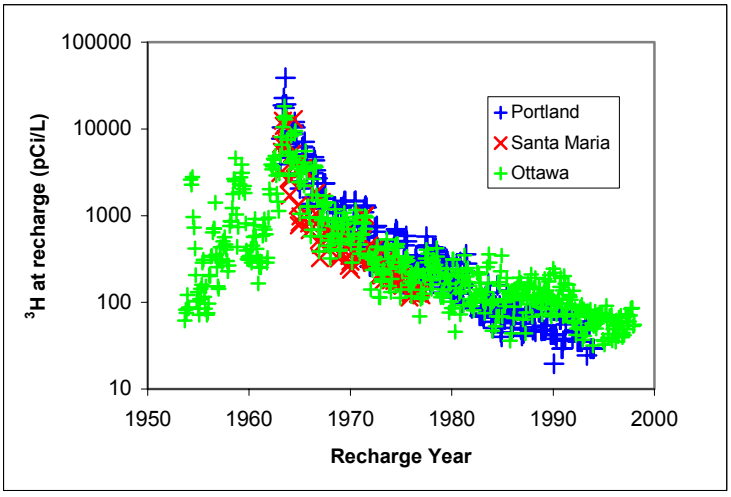



**Figure 1.** The tritium concentration measured in precipitation at three North American locations. Nuclear weapons testing introduced a large amount of tritium into the atmosphere in the 1960's, peaking in 1963.

Well water samples are always a mixture of water molecules with an age distribution that may span a wide range. A tritium-helium groundwater age is the mean age of the mixed sample, and furthermore, is the age only of the portion of the water that contains measurable tritium. Groundwater age dating has been applied in several studies of basin-wide flow and transport (Poreda et al., 1988, Schlosser et al., 1988, Solomon et al., 1992, Ekwurzel et al., 1994, Szabo et al., 1996).

Groundwater age is especially useful for determining the degree of stratification or conversely, of vertical transport in a layered aquifer system. The following examples illustrate this point. The Alameda County Water District (ACWD), in the East San Francisco Bay area of northern California artificially recharges $2.5 \times 10^{10}$ L of water per year. Recharge facilities consist of several abandoned quarries and of temporary reservoirs impounded behind inflatable rubber dams, in a creek channel that is adjacent to recharge ponds.

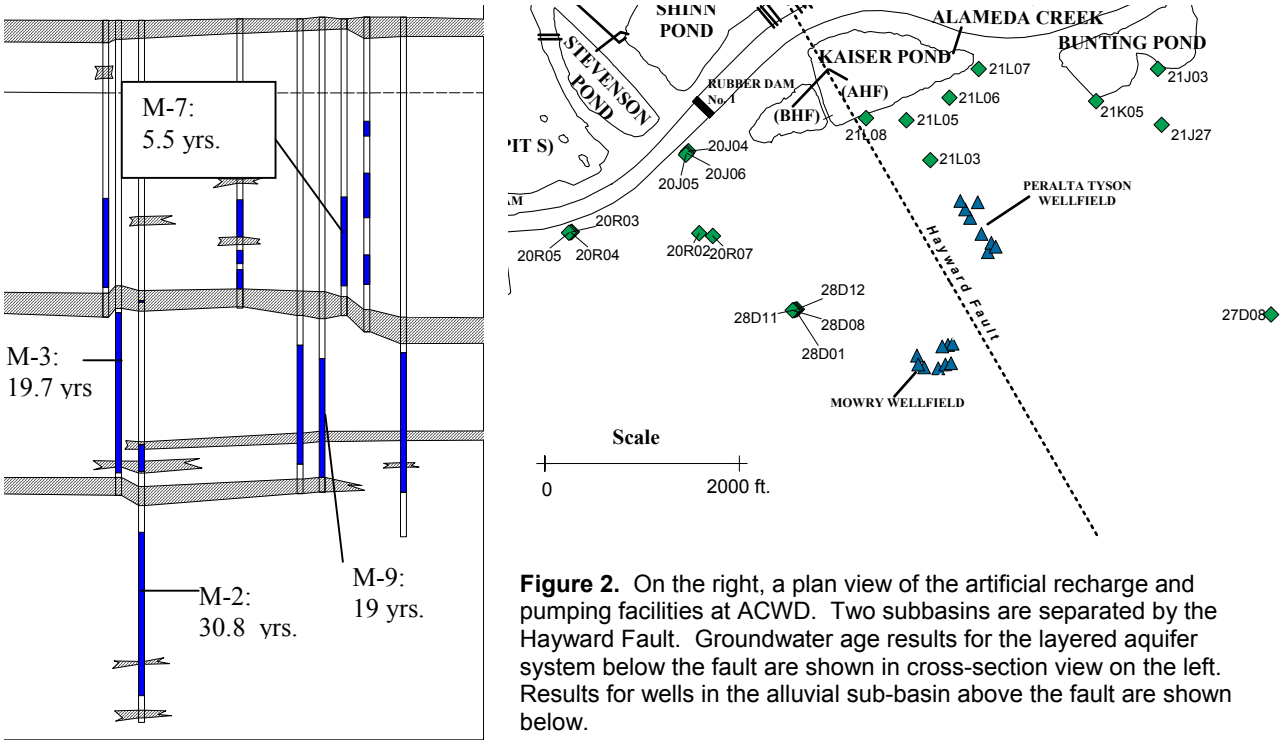
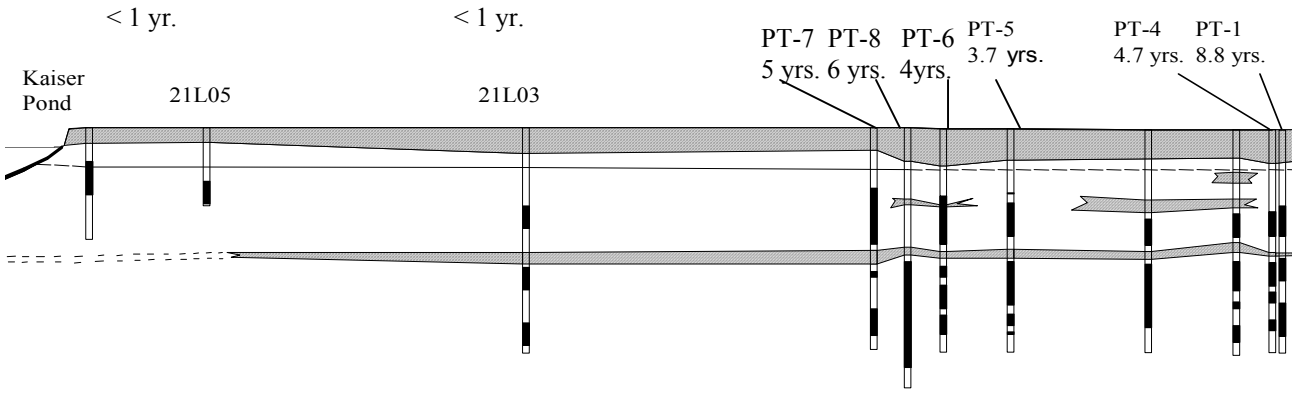



**Figure 2.** On the right, a plan view of the artificial recharge and pumping facilities at ACWD. Two subbasins are separated by the Hayward Fault. Groundwater age results for the layered aquifer system below the fault are shown in cross-section view on the left. Results for wells in the alluvial sub-basin above the fault are shown below.




The groundwater basin comprises alluvial deposits of the Quaternary period. Between periods of alluvial deposition, sea levels in San Francisco Bay rose and fine-grained sediment settled out to form aquicludes, separating the sands and gravels into distinct aquifer layers. The Hayward Fault, part of the San Andreas system, runs in a general north-south direction in the area, and hydraulically divides the groundwater basin into two sub-basins: the "Above Hayward Fault" (AHF) and "Below Hayward Fault" (BHF) sub-basins on the east and west side of the Hayward Fault, respectively (figure 2). About $10^{10}$ L of municipal pumping takes place in the two wellfields shown. Low permeability layers in the BHF sub-basin result in stratified groundwater, with mean ages of roughly 5, 20, and 30 years for the shallow, middle, and deep aquifers, respectively. Above the Hayward fault, groundwater flow is unimpeded, and wells produce a large volume of young groundwater with a mean age of 5 years.

Stable Isotopes as Tracers of Recharge Source and Evaporation

The minor stable isotopes of water molecules $^{2}H$ (deuterium, denoted as *D*) and $^{18}O$ vary in precipitation as a function of temperature, elevation and latitude (Craig, 1961; Ingraham & Taylor, 1991). In the Western U.S., extreme changes in elevation occur over relatively short distances. The net effect of isotopic fractionation during evaporation and condensation is that surface water from mountain watersheds has a significantly lower abundance of $^{18}O$ and D than coastal water (figure 3). The abundance of these isotopes in groundwater provides a fingerprint of the origin of the source water.

$\delta^{18}O$ in precipitation varies from approximately -4$^{o}/_{oo}$ along the Pacific coast to -17$^{o}/_{oo}$ in e.g., the Sierra Nevada Mountains and in the Colorado River Basin. Imported water used to supplement water supplies in areas of high water demand nearly always comes from colder and/or higher elevation sources, and has a distinctly lighter $\delta^{18}O$ signature than local water from within the water-poor watershed. Oxygen isotopes in groundwater thus provide a fingerprint that identifies the source water location.

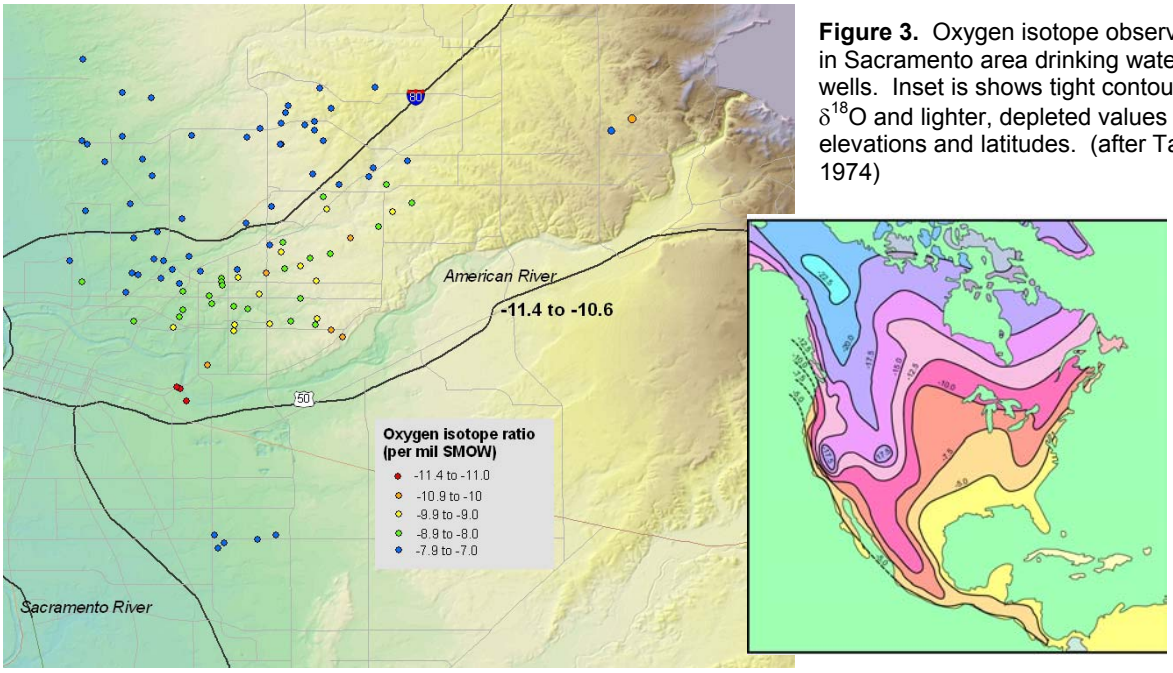



**Figure 3.** Oxygen isotope observations in Sacramento area drinking water wells. Inset is shows tight contours in $\delta^{18}O$ and lighter, depleted values at high elevations and latitudes. (after Taylor, 1974)

The oxygen isotope values ($\delta^{18}O$) delineate regions where groundwater is influenced by recharge of isotopically lighter ($^{18}O$ depleted) American River water and other areas where natural recharge introduces isotopically heavier ($^{18}O$ enriched) local water. Wells from the northern-most part of the Sacramento suburban area have an isotopic signature that is indicative of a local water source. The zone of influence of American River water extends from the areas adjacent to the river, where wells produce 100% recently recharged river water northward to Interstate 80. Local precipitation in the Sacramento area has a $\delta^{18}O$ value that averages approximately –7.5‰.

Several geochemical methods have been used to determine groundwater recharge rates including environmental tracers such as stable isotopes of oxygen and hydrogen and solute profiles. Solomon et al., (1993) determine recharge rates using tritium-helium groundwater ages in an area of nearly vertical recharge, and discuss in detail the limitations of the method with regard to dispersive effects of mixing and molecular diffusion, and with regard to complications posed by samples that come from near and before the tritium bomb pulse peak. In nested monitoring wells adjacent to the American river (figure 4), all samples are post bomb peak, and the other isotopic and chemical tracers suggest that mixing with non-river sources is minimal. Area 3 is an especially good profile for the purpose of estimating the long-term recharge rate, given the steadily increasing age and consistent $\delta^{18}O$ values that indicate a pure river source. A vertical recharge rate is calculated using a simple distance/time formula, and a recharge rate of 5.7 ft/yr (1.7 m/yr) is determined for the shallow zone to the deep zone. The rates determined here are estimates of the bulk, long-term recharge rate, and considerable variation is expected on daily and seasonal time scales. A large depression in groundwater levels to the north of the American River and groundwater production near the American River induce recharge at a higher rate than in the natural system. Away from the river, given the mean

annual rainfall in the Sacramento area (460 mm/yr) and high evapotranspiration rate for the Central Valley climate (65%), a recharge rate about 10 times lower than the rates calculated for river recharge is expected.

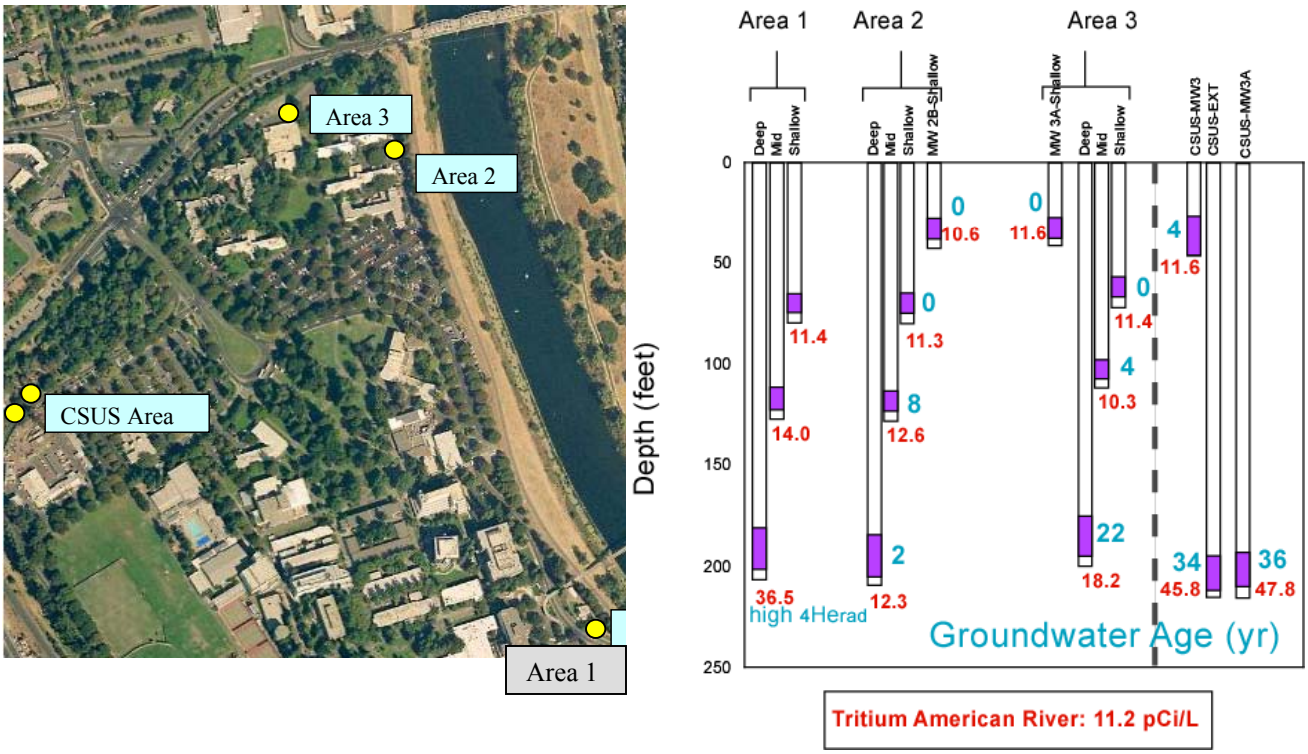



**Figure 4.** Study area adjacent to the American River in Sacramento, CA is shown on the left, with locations of well clusters as indicated. A slurry wall between the river and wells is apparently not effective in Area 2, where young water reaches to a depth of 200 ft (61m) (right schematic cross section with well screens shaded). Tritium concentrations and calculated tritium-helium groundwater ages show zero ages in the shallow section and increasing age and tritium concentration with depth at all areas except Area 2. Recharge rates are calculated from ages.

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